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An explanation of daytime discrete VLF emissions observed at Jammu (L = 1.17) and determination of magnetospheric parameters

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Abstract : The morphological characteristics of discrete VLF-emissions including diurnal, seasonal variations and spectral shapes, have been investigated based on the VLF data obtained during daytime at low latitude ground station Jammu (L = 1 17) for a span of two years (1997 1998) Different magnetospheric parameters like interaction length, wave magnetic field, bandwidth of the VLF emissions, rate of change of frequency (df/dt) of the recorded emissions, and number density of energetic electrons taking part in the generation of low latitude VLF emissions are determined to explain the spectral forms of the observed emissions at Jammu Comparisons of the theoretical parameters are made with the observed parameters of the recorded emissions at Jammu. The estimated parameters are in good agreement with the measured parameters.

Keywords : VLF emissions, whistlers, cyclotron resonance.

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1. Introduction

Very Low Frequency (VLF) emissions (or VLF ionospheric noise) like whistler, is a class of natural radio phenomenon [1]. These emissions have over the past decades become a very important diagnostic tool for probing the plasmasphere and beyond. These emissions although less well understood than whistlers are believed to have origin in the ionosphere-magnetosphere coupled system and may be due to plasma instabilities or insitu electromagnetic radiations from high energy particles. In fact, several types of VLF emissions are often observed in close association with whistlers. The group of VLF emissions is itself divided into two groups : (1) continuous emissions in both time and frequency which tend to maintain a steady state. Hiss, resonance bands, and noise bands near the ion gyrofrequencies seem to fit this type [1], (2) discrete emissions often with a repetitive and even periodic character which tend to be transient. Chorus, periodic emissions and various other transient discrete emissions such as hooks, psuedo-whistlers, and psuedo-noses have been reported at high latitudes [2]. Low altitude satellite observations have enabled us to determine the global distribution of VLF emissions within the ionosphere and it is found that VLF emissions of magnetospheric origin occur predominantly in the two characteristic latitude regions : high latitude (auroral zone) and medium latitude (around plasma pause) [3].

Unlike mid and high latitude emissions, low latitude daytime VLF emissions have not been used much for exploring the inner magnetosphere. The main reason being the fact that the propagation characteristics of daytime VLF emissions in the low-latitude ionosphere are not properly known because of the scarce satellite and ground-based observational results. Hence, the mechanism of their generation source and propagation are quite far from perfect understanding. Therefore, an understanding of the generation mechanism of these VLF emissions observed at low-latitudes could be most useful for inferring the properties of high energy trapped electrons. During the course of our analysis of a huge amount of VLF data collected in January 1997 to June 1998 at Jammu (geomag. lat. 22°26' N; L = 1.17) we have found excellent records of discrete chorus emissions which we use here with a discussion of their most probable generation mechanism.

The experimental observation made so far on these VLF emissions strongly support the suggestion made earlier that these emissions are produced in the magnetosphere near geomagnetic equator by trapped energetic electrons. These electrons couple energy to whistler-mode waves through a feedback mechanism based on cyclotron resonance. The generated waves travel to the earth in the field-aligned ducts [4]. The purpose of this paper is to explain the spectral forms of discrete VLF emissions recorded at Jammu using the concepts of cyclotron resonance and feedback as suggested by Helliwell [4]. This paper is divided into three main parts. Following the introduction in Section 2 is data selection and analysis. The Helliwell's Theory [4] used to explain the spectral forms of discrete VLF emissions observed at Jammu is outlined in Section 3. Finally comparisons of the theory with observations are made in Section 4. It is shown that the theory can account for the observed spectral forms. An attempt has also been made to determine the magnetospheric parameters taking part in the generation process of discrete VLF emissions recorded at Jammu during daytime.

2. Data selection and analysis

A new ground based VLF station at Jammu was set up in the year 1996 and the recording of VLF waves was started in the month of December 1996 on a routine basis. The VLF emissions were received, as usual by a *T*-type antenna 25 m high, suitably amplified by transistorised pre- and main-amplifiers and recorded using a tape recorder. The magnetic tapes containing VLF data were analysed at the Atmospheric Research Laboratory, BHU, Varanasi and Central Electronics Engineering Research Institute, New Delhi, India.

At low-latitudes, the VLF emission occurrence rate is low and sporadic. But once it occurs its occurrence rate becomes comparable to that of mid latitudes [5]. Similar behaviour has also been observed at our newly started ground based station Jammu. For the present study we have chosen daytime VLF emissions recorded at Jammu during the yeats 1997 and 1998. A huge amount of data of VLF emissions was collected during these years. From the analysis of the data collected, it is found that discrete VLF emissions occur frequently during noon and afternoon. A sample histogram of diurnal variations of VLF occurrence rate at low-latitude station Jammu is shown in Figure 1. It is clear from Figure 1 that discrete chorus emissions recorded at Jammu mainly in the afternoon is in agreement with that observed at high latitude stations around 1200 LT [6–8]. Figure 2 depicts a histogram of the seasonal variation of the occurrence rate of VLF discrete emissions at

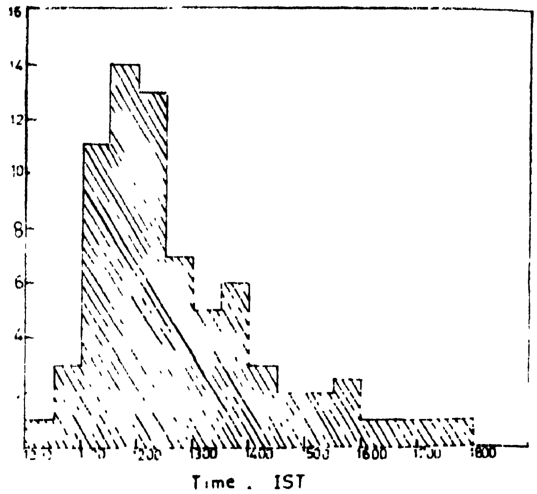

Figure 1. Histogram of diurnal variation of daytime discrete VLF emissions observed at Jammu (L = 1 17).

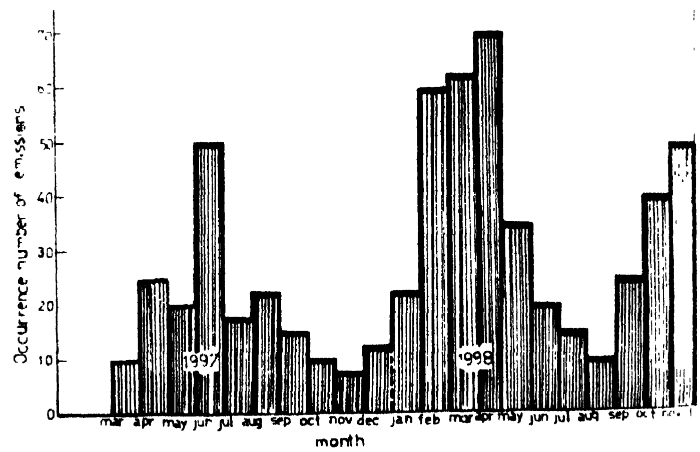

Figure 2. Histogram of seasonal variation of daytime VLF emissions.

Jammu for the year 1997 and 1998. Their rate of occurrence is extremely high in the month of June in year 1997 and in the months of March, April and December of the year 1998. Chorus is aurally perceived as a "birds dawn chorus", as was first suggested by K. W. Tremellen in England [9]. Therefore, normally the most intense chorus events should be observed at approximately 0600 LT (local time) by its term "dawn", whereas discrete VLF emissions during daytime at Jammu are observed in the afternoon as shown in Figure 1. It is clear that the characteristics of VLF emissions at low-latitudes are similar to those of high-latitude emissions, but differ from that of mid-latitude stations where these emissions are observed typically at 0600 LT.

A typical spectrum of the discrete VLF emissions recorded on June 3, 1997 during daytime between 1130 IST to 1800 IST (Indian Standard Time), at Jammu out of a huge number of data is shown in Figure 3. Figure 3(a) contains four chorus risers with a background hiss band (1 kHz to 2 kHz). The mean upper boundary freqency for these risers is 5 kHz. In Figure 3(b) we find four chorus riser emissions (mean upper boundary frequency of 5.4 kHz). The hiss band has been observed at a frequency range 1.5 kHz to 4.5 kHz. Some short riser discrete chorus emissions have been observed in Figures 3(c) and 3(d), having mean upper boundary frequencies of 4.5 kHz and 3.5 kHz. All these figures show a simultaneous occurrence and unstructured type (hiss). The events in Figure 3 correspond to a magnetically quiet day. The spectrograms of some other significant discrete VLF emissions are shown in Figure 4 observed during daytime (afternoon) on March 19, 1998 (Figure 4a) and April 7, 1998 (Figure 4b). Two long risers with mean upper boundary frequency around 4 kHz are shown in Figure 4(a). The spectra in Figure 4(b) shows combination type discrete VLF emissions with inverted hooks, rising and falling tones. The spectral forms recorded on March 19, 1998 [Figure 4(a)] correspond to a magnetically quiet day with the sum of K_p indices as 7 ($\Sigma K_p = 7$) and the recordings of April 7, 1998 [Figure 4(b)] correspond to the quiet day with sum of K_p indices as 15 ($\Sigma K_p = 15$). Different slopes and varying intensities have been observed with sharpness and diffuseness varying from event to event.

3. Theoretical considerations

Experimental observations show a strong evidence that discrete VLF emissions are generated near the magnetospheric equator by trapped energetic electrons. The observed correlations between chorus emissions and energetic electrons at mid and high latitudes suggest that these electrons play a key role in the generation of VLF emissions [10]. Brice [11] suggested nonconvective transverse instability between whistler waves and counter streaming energetic electrons as basic mechanism for the generation of chorus emissions. Burton [12] pointed out that chorus emissions are observed only when the anisotropy of energetic electrons was finite. This is consistent with the hypothesis that these emissions are excited due to transverse resonant cyclotron instability. Helliwell's Theory [4] based on extension of transverse resonance condition explains some of the characteristic features of the observed VLF emissions. Recently Nunn and Sazhin [13] developed a theory based on the interaction between VLF hiss and energetic electrons to explain the similarities between fine structures of chorus and hiss emissions.

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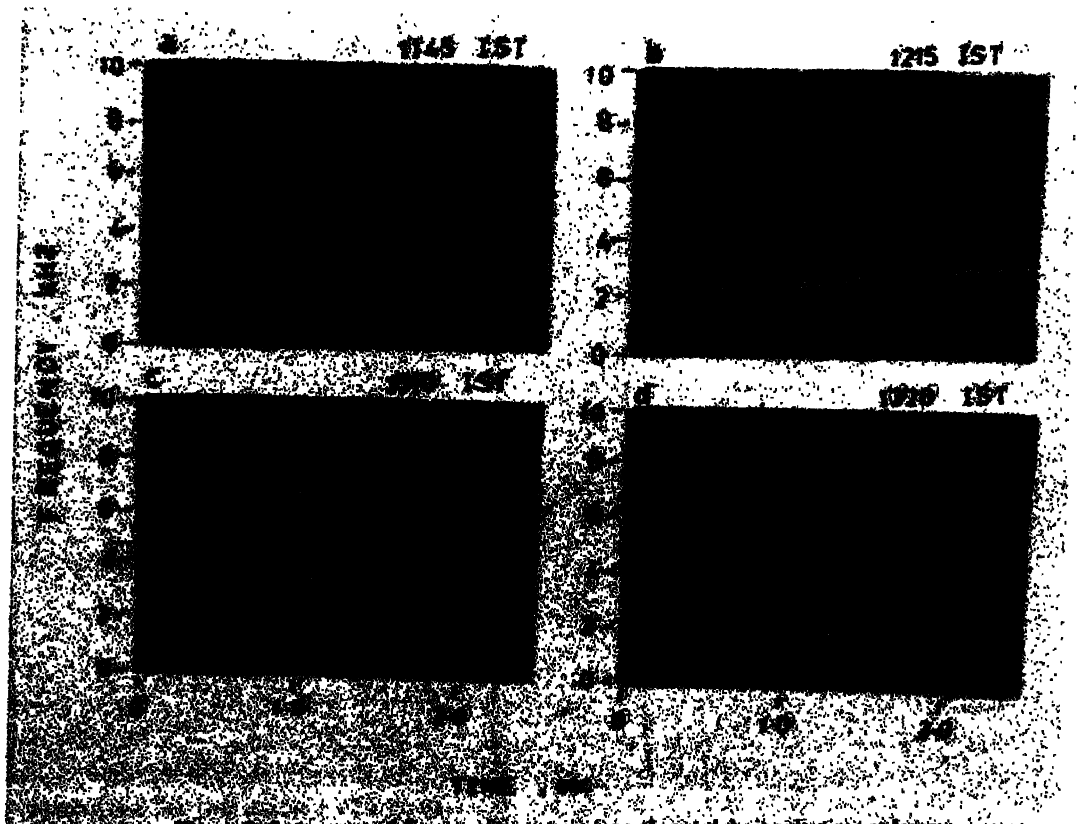

Figure 3. [illegible] of discrete VLF emissions observed during daytime at Jammu.

The first attempt to explain spectral shapes of discreate VLF emissions with the help of a theory was made by Gallet and Helliwell [14]. His theory was based on an analogy with a travelling tube amplifier. In this mechanism, ambient whistler mode noise provided the input signal that was amplified by an assumed bunch of trapped electrons whose streaming velocity equalled the longitudinal component of the wave velocity. The next attempt was made by Dowden [15]. This suggestion also postulated bunches of electrons, but assumed that they radiated Doppler-shifted, backward-travelling whistler mode waves. Several spectral forms were explained by this mechanism. Another mechanism employing particle bunches was suggested by Ellis [16] and is based on anomalous Doppler radiation. Both these theories failed to explain long-enduring quasi-constant tones. The bunch theory was also applied to the phenomenon of periodic emissions, which consist of a series of similar equally spaced discrete emissions [15]. From the experimental evidence Helliwell [17] and Helliwell and Brice [18] have shown that periodic emissions are generated through triggering by emissions echoing in the whistler mode and not by mirroring bunches of particles. Therefore, particle-bunch theory was ruled out as an explanation of periodic emissions. In order to avoid the difficulties of the bunch theory Brice [19] suggested the transverse resonance instability between whistler waves and counter streaming energetic electrons. None of these theories has been able to explain both the narrow bandwidth and the variable frequency of discrete VLF emissions. Helliwell [4] developed a theory based on extension of the transverse resonance condition proposed by Brice [19,11] which could explain most of the characteristics of VLF emissions recorded on the ground station.

Although at present we do not have a unified accepted general theory of VLF emissions at low latitudes, we find that Helliwell's Theory [4] based on gyroresonance interaction between energetic streaming electrons and whistler mode waves travelling in the opposite direction is able to explain most of the spectral shapes of discrete VLF emissions recorded at Jammu.

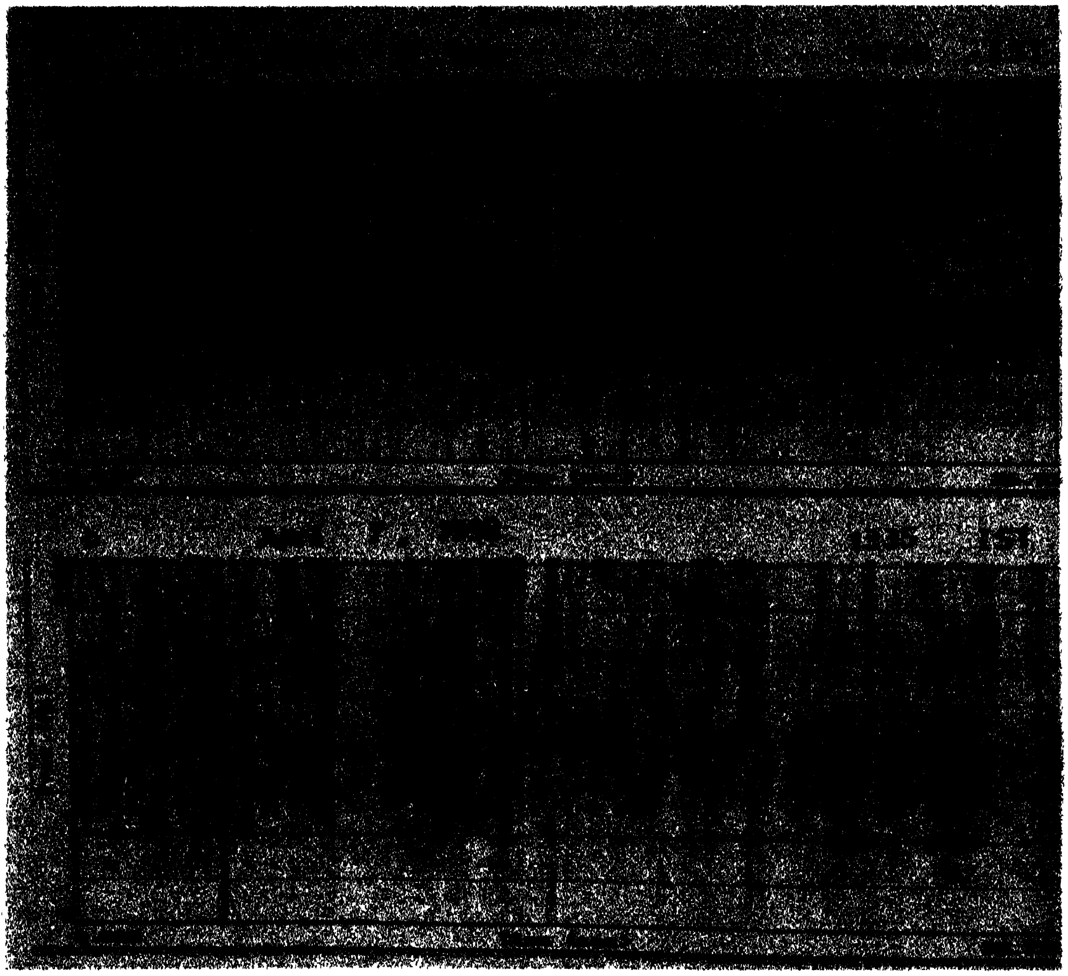

Figure 4. Sonograms of discrete chorus emissions observed during daytime at Jammu.

The spatial variations of the electron gyrofrequency and the Doppler-shifted wave frequency is matched in Helliwell's Theory [4]. This condition is known as 'consistent-wave' condition and ensures that the time during which an electron is in resonance with the generated wave will be maximum, and hence the energy delivered to the wave can be expected to maximize also. Application of the consistent-wave condition leads directly to a description of the frequency-time variation as seen by a fixed observer. It is then assumed that the oscillation takes place in a region that may be fixed in space or may drift forward or backward. This is called 'interaction' region and in which a constant wave amplitude and a constant transverse electron current is seen. The transverse electron current depends on the phase bunching produced by the magnetic field of the wave, while the wave in turn is radiated by the transverse currents. The phase bunching of electrons produces a spatial maximum in the transverse current density which in turn generates the observed radiation [4].

Using a simple phasing criterion as discussed above, Helliwell [4] has derived the expressions to estimate the total length of the resonance region (l_R), to obtain a quantitative expression for the change of frequency with time (df/dt), to obtain the bandwidth of radiation (Δf), the wave magnetic field intensity (B_w), and the concentration of electrons in the transverse current stream (N) taking part in the generation process of VLF emissions are given by (see for details Helliwell, 1967) [4] :

$$l_R = 5.85\times10^5(1-\lambda)^{1/2}/\left(f_N^{1/3}f_{H0}^{2/9}\lambda^{1/6}\right)\ \text{Km} \tag{1}$$

$$\begin{aligned} df/dt &= [54cf_{H0}^2 l_R \lambda^{3/2}/R_m^2 f_N] \\ &\times[(1-\lambda)^{3/2}/2(1+2\lambda)^2] \\ &\times[1+((1-\lambda)/3)\tan^2\alpha]\ \text{Hz/sec} \end{aligned} \tag{2}$$

$$\Delta f = 1.7 f_{H0}\left(l_R/R_m\right)^2\ \text{Hz} \tag{3}$$

$$B_w = 5.8\times10^{-13}\left[f_{H0}^{13/9}(1-\lambda)/f_N^{4/3}\lambda^{2/3}\right]\cot\alpha\ \text{webers}\ m^{-2} \tag{4}$$

$$N = 15\pi B_w/16\mu_0 l_R q v_\perp \quad \text{el m}^{-3} \tag{5}$$

where frequency is expressed in Hz, $\lambda = f/f_H$, f is the wave frequency, f_{H0} = electron gyrofrequency at the top of the path, f_N = electron plasma frequency, c = the velocity of light, R_m = distance to the top of the path from earth's center, α = pitch angle at the centre of interaction region, $\mu_0 = 4\pi\times10^{-7}$ Weber/Henry permittivity of free space, q = charge on electron, and $v_\perp$ = perpendicular velocity of the electron $= 0.577(c/f_N)\left[(f_H-f)^{3/2}/f^{1/2}\right]$, where f_H = electron gyrofrequency.

Using equations (1) to (5) the various magnetospheric parameters are determined for the latitude of Jammu (L = 1.17) in order to explain the observed spectral shapes of the discrete VLF emissions recorded at Jammu during daytime. It is shown that the theory can account for the observed spectral forms at Jammu. The variation of resonance length (l_R) with wave frequency computed from eq. (1) is shown in Figure 5 for $f_N = 2.70\times10^3$ kHz, $f_{H0} = 560\times10^3$ kHz (L = 1.17). It is clearly seen from Figure 5 that resonance length depends mainly on λ and has values roughly between 402 Kms and 633 Kms for the frequencies of principal interest. Closely related to resonance length is the bandwidth of radiation. The calculated value of the magnitude of the bandwidth radiated from eq. (3) comes out to be about 3 kHz. The computed value of the slope (df/dt) of an emission from eq. (2) comes out to be about 2 kHz/sec which is within the range of observation. This value is found to vary with α. The value of wave magnetic field is obtained from eq. (4) and is found to lie in the range of 0.13×10^{-14} and 0.36×10^{-14} weber m^{-2}, which is substituted in eq. (5) to find N. The corresponding

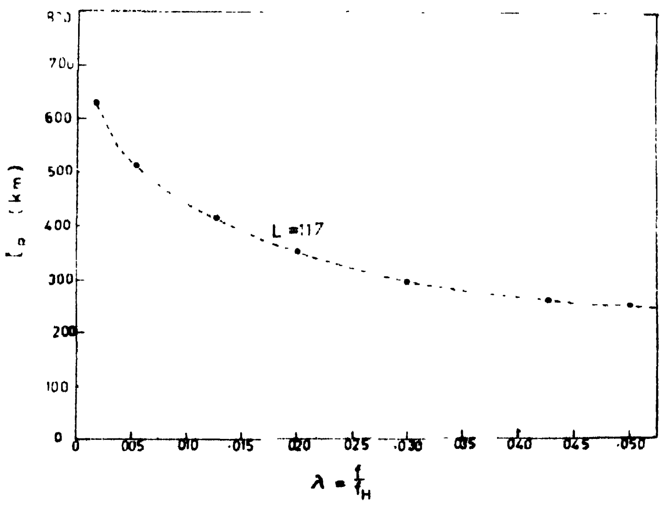

Figure 5. Graph depicting interaction length *versus* normalised wave frequency for l_R = 1.17.

concentration of electrons in the current system taking part in generation of VLF emission is found to be about 0.1 m^{-3}. All the computed parameters using Helliwell's equations are found to lie almost within range of our observed parameters of the discrete VLF emissions.

4. Results and discussion

Morphological features of discrete chorus emissions throughout the magnetosphere have been investigated by several earlier workers based on ground and satellite measurements [20–27]. These studies have revealed that chorus is observed mainly at L-values between plasma pause and magnetopause at all local times (LT), but predominantly in the dayside magnetosphere. But no systematic studies have been done at the low latitude during daytime, because of the scarce satellite and ground-based observational results. A statistical study of the discrete chorus emissions recorded at Jammu have been carried out systematically on the data collected during the years 1997 and 1998. This study has revealed that the discrete chorus emissions at low-latitudes during daytime is observed mainly in the afternoon local time (LT) and the occurrence rate is maximum during the months of May/June as shown in Figures 1 and 2.

The daytime discrete chorus emissions observed at Jammu differ markedly in frequency and rate of change of frequency with time (*df/dt*) from those of chorus emissions observed at mid and high latitudes. The possibility that these emissions are high latitude discrete chorus emissions which have propagated to our low-latitude ground station Jammu in the Earth-Ionosphere waveguide of propagation is ruled out as there is a strong absorption band in the frequency range around 2 kHz. Further, the possibility that these emissions are generated at high L-values in the vicinity of plasmapause and propagated to our ground station after successive magnetospheric reflections in a manner similar to those of extremely low frequency (ELF) hiss observed by satellites in the inner zone does not seem to be tenable [28,29]. This is because at the frequency of these emissions, the attenuation losses during various magnetospheric reflections could be high and waves could not be detected on the ground. Although the exact losses have not been calculated, a rough estimate can be made from the work of Kimura [30,31]. He has shown from ray tracing computations in a model ionosphere that the amount of attenuation suffered by the waves of frequency 1 kHz from 300 Kms at 30° N reaching $L = 3$ after 12 successive reflections is about 6 dB. If we include 4 dB losses suffered in the lower region of the ionosphere, then the total loss will be about 10 dB. To reach the plasmapause near $L = 4$, the waves have to undergo some more reflections and consequently suffer more attenuation than 10 dB. Since the attenuation increases with frequency the waves of chorus emissions generated near plasmapause may not be observed on the ground as they will suffer much higher attenuation than 10 dB. In addition to this, the wave normal angles of each wave at the base of F-region of ionosphere are such that the downward waves are unlikely to penetrate the lower ionosphere and reach to ground.

It is therefore, believed that discrete chorus emissions observed at Jammu during daytime are generated in the equatorial plane at the top of the field line corresponding to Jammu, near the inner zone radiation belt (L ~1.2). The gyroresonance between whistler mode waves and energetic streaming electrons as suggested by Helliwell [4] seems to be the possible generation mechanism of discrete chorus emissions recorded at Jammu for the reason that this mechanism has been found to account for the frequency-time spectra of middle and high latitude discrete chorus emissions adequately. To test Helliwell's theory as the possible generation mechanism for those emissions at low-latitude we have computed various parameters like interaction length (l_R) shown in Figure 5, slope df/dt, bandwidth of the emissions (Δf), wave magnetic field B_w, the concentration of electrons in the transverse current stream (N) taking part in the generation process of VLF emission observed at Jammu during daytime. All these computed parameters using Helliwell's Theory [4] are comparable to that of the observed parameters satisfactorily. There is one to one correspondence between calculated parameters as shown in Table 1.

Table 1 Emission parameters.

Plasma frequency	$f_N = 2.7 \times 10^3$ kHz
Bandwidth of the discrete Chorus emission	df/dt ~ 2 kHz/sec

Further experimental studies of discrete chorus emissions during daytime are required to contribute a more detailed understanding of this phenomenon. We believe that at this stage the highest priority should be given to the theoretical research. The latter could enable us to improve our understanding of the formation of the chorus elements and their interaction with magnetospheric electrons, and thus could stimulate further experimental research.

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